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Xianghu Li

Chinese Academy of Sciences & University of Nebraska-Lincoln

Qi Hu

University of Nebraska-Lincoln

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Research Article

Spatiotemporal Changes in Extreme Precipitation and Its Dependence on Topography over the Poyang Lake Basin, China

Xianghu Li ^{1,2} and Qi Hu²

¹Key Laboratory of Watershed Geographic Sciences, Nanjing Institute of Geography and Limnology, Chinese Academy of Sciences, Nanjing 210008, China

²School of Natural Resources, Department of Earth and Atmospheric Sciences, University of Nebraska-Lincoln, Lincoln, NE 68583, USA

Correspondence should be addressed to Xianghu Li; lxh8010@163.com

Received 22 May 2018; Revised 21 December 2018; Accepted 6 January 2019; Published 3 February 2019

Academic Editor: Anthony R. Lupo

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Spatiotemporal changes in extreme precipitation at local scales in the context of climate warming are overwhelmingly important for prevention and mitigation of water-related disasters and also provide critical information for effective water resources management. In this study, the variability and trends of extreme precipitation in both time and space in the Poyang Lake basin over the period of 1960–2012 are analyzed. Also, changes in precipitation extremes with topography are investigated, and possible causes are briefly discussed. The results show that extreme precipitation over the Poyang Lake basin is intensified during the last 50 years, especially the increasing trends are more significant before the end of the 1990s. Moreover, high contribution rates of extreme precipitation to the total rainfall (40–60%) indicated that extreme precipitation plays an important role to the total water resources in this area. The precipitation extremes also exhibited a significant spatial dependence in the basin. The northeastern and eastern areas are exposed to high risk of flood disaster with the higher frequency of extreme precipitation events. In addition, the distribution of precipitation extremes had a clear dependence on elevation, and the topography is an important factor affecting the variability of extreme precipitation over the Poyang Lake basin.

1. Introduction

One aspect of the changing climate is change in extreme weather and climate events at regional and global scales [1, 2]. Adverse impacts on the society and environment from more frequent and severe weather and climate events in the recent decade have raised concerns of the public, governments, and academic communities [3]. This is especially true for extreme precipitation events. Mounting evidence is indicating that a warming climate could have more frequent precipitation extremes [4–8].

Global scale extreme precipitation variability and trend have shown significant change; the frequency of heavy precipitation events in many areas, particularly in mid-latitude regions, has increased [9, 10]. For example, Asadieh and Krakauer [11] evaluated trends in global daily precipitation extremes and found that 66.2% of their studied

grid cells show a positive trend during the past 110 years in South America, Australia, and India, 18% of which are statistically significant at the 95% confidence level. Similar changes are also reported in other studies [12, 13]. Tank and Konnen [14] suggested that most of indices for extreme precipitation events have increasing trends in Europe during 1946–1999. Hoerling et al. [15] showed that the increases in heavy precipitation in terms of frequency and intensity have been accelerated after 1979 in the northeast United States. Boo et al. [16] reported an increasing in the number of days and intensity of heavy precipitation over the Korean Peninsula. Similar results have also been reported in studies of Arnbjerg-Nielsen et al. [4] and Willems et al. [5].

However, because of large differences in regional geographic and atmospheric characteristics, the variability of precipitation extremes is different across geographical regions [17]. For example, results of variability of precipitation

extremes in the Asian Pacific region [18] and Canada [19] showed no systematic trends in frequency and intensity of extreme precipitation events. Only insignificant increases were found in consecutive wet days in the Arab region, the Greater Horn of Africa [20], and the east Pacific coast of South America [21]. To the other end, Haylock and Nicholls [22] and Piccarreta et al. [23] have shown that the extreme precipitation underwent a downward trend in Western Australia and the Mediterranean area from 1951 to 2010. As summarized in IPCC [24], increases in the amount of precipitation are at high latitude regions and decreases in many subtropical regions. In addition, Wang et al. [25] showed that the increasing precipitation was more prominent at higher elevations, while the decrease was more significant at lower elevation.

In China, extreme precipitation events have also exhibited strong regional differences because of the complexity of topography and climate [26–29]. However, the spatiotemporal heterogeneity of precipitation extremes derived from large-scale datasets or global model outputs is coarse or even incorrect at catchment scales. For example, many studies have reported that extreme precipitation events in the past decades have increased in most regions of China [30–34]. Upward trends were found in northwest China, southeast coastal regions, and the Yangtze River basin, whereas significant downward trends were found in central, northern, and northeastern regions of China and along the Yellow River basin [3, 35–37]. But at local scales, the changing trends of precipitation extremes were more complex and some were not as described by the average trend of a region. For example, precipitation extremes in the middle and lower reaches of the Yangtze River basin show statistically significant positive trends [3, 37]. However, no clear trend has been identified in the upper river basin [36]. Su et al. [38] and Guo et al. [29] pointed out that variations in extreme precipitation showed distinctively catchment scale characteristics and no one pattern fitted in the entire Yangtze River basin. Therefore, quantifying the trends and variability in precipitation extremes at the basin and catchment scale can provide additional and useful information for water resources management and mitigation strategies for flood or drought [39].

In the middle reach of the Yangtze River is the largest freshwater lake basin in China, the Poyang Lake basin (Figure 1) [40]. It has a strategic importance in sustainable development of the economy in southeast China. The basin is also one of the most frequently flooded areas in China. Frequent severe floods in the last several decades have caused enormous damage to the environment and the economy and threatened the lives of approximately ten million people in the region [41, 42]. Severe flood events in the Poyang Lake basin are mainly ascribed to abnormal climate condition [43]. For example, in the rainy seasons of 1998 and 1954, precipitation was significantly higher than the average in the middle Yangtze River basin (with the excessive June–July rainfall of 300 mm and 220 mm, respectively) [44]. Hu et al. [45] and Guo et al. [46] also found that the increase in flood frequency and severity in the Poyang Lake basin in the 1990s was partially attributable to

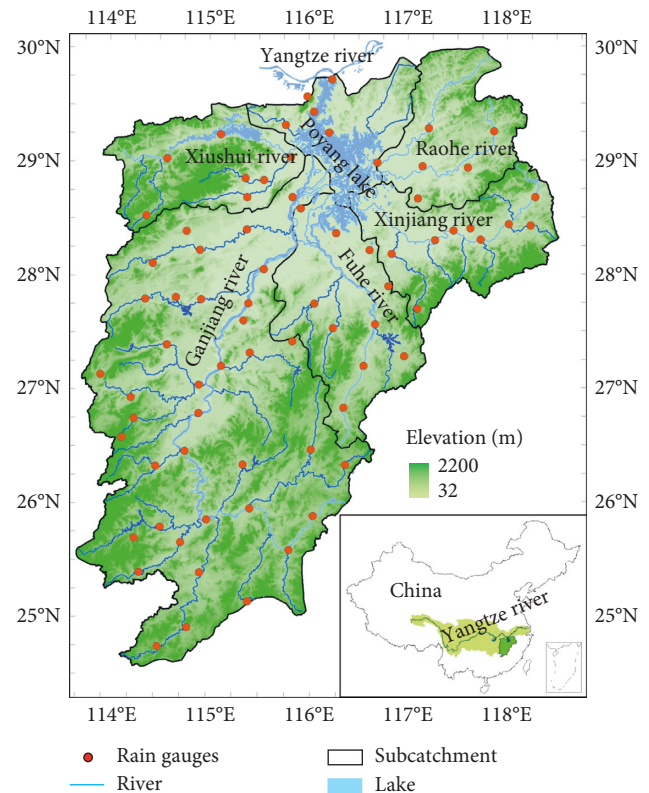


FIGURE 1: Location of study area and the distribution of rain gauges (reproduced from Li and Ye [40], under the creative commons attribution license/public domain).

the southward shift of the major warm-season rain band to the south of the Yangtze River basin. This rain band brings more extreme precipitation events to the Poyang Lake basin. Thus, a better understanding of variations in precipitation extremes in the context of climate change in the Poyang Lake basin is vital to improve flood prediction and mitigation in this area [47].

Among many aspects related to the development of extreme rainfall events is the orographic effect. Certain orographic settings confine the atmospheric circulation and configure intense lifting and favor extreme rainfall. Zhang et al. [48] suggested that the analysis of changes in precipitation extremes should take into account the orography of a study region. Although the orographic role in severe precipitation has long been recognized, very few of previous studies have examined such role in the Poyang Lake basin. In this study, we extend the previous findings regarding the spatiotemporal changes in precipitation extremes and examine the role of the orography of the lake basin in precipitation extremes. Our main objectives are (1) to identify and analyze the trends and variability of extreme precipitation events in time and space in the Poyang Lake basin during 1960–2012 based on a suite of measures of extreme precipitation and (2) to investigate the dependence of precipitation extremes on topography in the basin. Outcomes of this study are expected to provide a better understanding of variations in heavy and extreme precipitation events in the Poyang Lake basin for water resource management and disaster prevention and mitigation.

2. Study Area and Data

The Poyang Lake basin is located in the middle and lower reaches of the Yangtze River, China, and the lake receives water primarily from five subcatchments in its basin (i.e., Xiushui, Ganjiang, Fuhe, Xinjiang, and Raohe) (Figure 1). The total drainage area of the lake is $16.22 \times 10^4 \text{ km}^2$, accounting for 9% of the drainage area of the Yangtze River basin. The topography in the basin is complex, and the elevation varies from 2200 m (above sea level, asl) in highly mountainous regions to about 30 m asl in alluvial plains downstream of the major watercourses and around the lake. The wide alluvial plains surrounding the lake and the broad alluvial valleys of the tributary streams are important rice-growing regions in the Jiangxi province [49]. The boundary of the basin largely follows the administration boundary of the Jiangxi province, which has a population of 45 million (in 2012) [50]. The Poyang Lake basin has a subtropical wet climate influenced by the East Asian monsoon. The mean annual rainfall is 1626 mm for the period of 1960–2012, of which more than 50% falls in March to June, with a peak in June. Annual precipitation in the Poyang Lake basin shows a wet season and a dry season and a short transition period in between [49]. The water surface area of the lake can exceed 3000 km^2 in the wet season [42] and shrink to $<1000 \text{ km}^2$ during the dry season [51]. The spatial distribution of rainfall in the basin is uneven, with the ratio of maximum to minimum ranging from 1.65 to 2.51. The highest annual rainfall is observed at Wuyuan station (3036 mm) in 1998 and the lowest at Hukou station (776 mm) in 1978. The annual mean temperature is 17.6°C , with an average of 27.3°C in summer (June–August) and 7.1°C in winter (December–February) [50].

In this study, the observed daily rainfall data at 75 rain gauges in the Poyang Lake basin during the period of 1960–2012 as well as the elevation of each rain gauge are collected from the National Meteorological Information Center of China. The locations of those rain gauges are shown in Figure 1. Daily rainfall data are used to examine variability of precipitation events in the basin. The gauge elevation data are used to investigate the relationship of extreme precipitation with elevation and topography. The qualities of these data have been tested, and the data have been widely used in many previous studies [40, 46, 49, 50, 52–54].

3. Methods

3.1. Threshold of Extreme Precipitation Events. Absolute threshold and the percentile methods have often been used to determine extreme precipitation events [55–57]. We use the daily precipitation data from 1960 to 2012 at the 75 stations and a percentile method to determine the threshold of extreme precipitation. The average threshold of extreme precipitation at 90, 95, 97, and 99 percentile is 14.3, 25.4, 34.6, and 56.5 mm per day, respectively (Table 1). The threshold of extreme precipitation events determined by the percentile can be different using different percentile points. There is a great deal of debate on which percentile point should be used to determine the threshold of extreme daily

TABLE 1: Threshold of extreme precipitation at different terciles in the Poyang Lake basin.

Percentile (%)	90	95	97	99
Precipitation (mm/day)	14.3	25.4	34.6	56.5

precipitation because the selected terciles have inherent subjectivity [58]. According to the precipitation classification suggested by the China Meteorological Administration, an event with rainfall exceeding 25.0 mm in a 24-hour period is classified as a heavy precipitation event. That rate is close to the widely used 95th percentile of daily precipitation. Therefore, the value of 25.0 mm in a 24-hour period is used as the threshold of extreme precipitation in the Poyang Lake basin in this study.

3.2. Indices of Extreme Precipitation. The Expert Team on Climate Change Detection and Indices (ETCCDI) has recommended a list of precipitation extreme indices for use to estimate precipitation extremes. Those indices have been widely used in climate extreme studies [59–61]. In this study, eight indices from the list are selected to depict extreme precipitation events in the Poyang Lake basin. These indices can be divided into three categories: (1) threshold indices, including annual extreme precipitation days (EPDs), annual extreme precipitation amount (EPA), annual average extreme precipitation intensity (EPI), and extreme precipitation rate of contribution (EPR); (2) duration indices, including consecutive dry days (CDDs) and consecutive wet days (CWDs); and (3) absolute indices, including maximum one-day precipitation amount (Rx1d) and maximum five-day precipitation amount (Rx5d). Detailed descriptions of these indices are provided in Table 2.

3.3. Trend Analysis. The trends of extreme precipitation events in the Poyang Lake basin are evaluated using the Mann–Kendall (M-K) test [62, 63]. The M-K test is a rank-based nonparametric method, which is robust against the influence of extreme data and good for use with biased variables. It has been used for trend detecting in climatologic and hydrologic time series [49, 64].

For any samples of n variables, $x_1, x_2, x_3, \dots, x_n$, the accumulative number n_i of samples with $x_i > x_j$ ($1 \leq j \leq i$) should be calculated [49]. A statistical parameter d_k can be calculated from the following equation:

$$d_k = \sum_{i=1}^k n_i \quad (2 \leq k \leq n). \quad (1)$$

Under the null hypothesis of no trend, d_k is asymptotically normally distributed with expected mean value $E(d_k)$ and variance $\text{Var}(d_k)$ as follows:

$$E(d_k) = \frac{k(k-1)}{4}, \quad (2)$$

$$\text{Var}(d_k) = \frac{k(k-1)(2k+5)}{72}.$$

With the above assumption, the normalized variable statistic $Uf(d_k)$ is calculated from the following equation:

TABLE 2: Definitions of 8 precipitation extreme indices used in this study.

Categories	Indices	Description	Units
Threshold indices	The annual extreme precipitation days (EPDs)	Annual count of days when daily precipitation \geq the threshold of extreme precipitation	days
	The annual extreme precipitation amount (EPA)	Annual total precipitation amount when daily precipitation \geq the threshold of extreme precipitation	mm
	The annual average extreme precipitation intensity (EPI)	EPA divided by EPD	mm/day
	The extreme precipitation rate of contribution (EPR)	Contribution of extreme precipitation to the annual total rainfall	%
Duration indices	The consecutive dry days (CDDs)	Maximum number of consecutive days with daily precipitation < 1 mm	days
	The consecutive wet days (CWDs)	Maximum number of consecutive days with daily precipitation ≥ 1 mm	days
Absolute indices	The maximum one-day precipitation amount (Rx1d)	Annual maximum 1-day precipitation	mm
	The maximum five-day precipitation amount (Rx5d)	Annual maximum consecutive 5-day precipitation	mm

$$Uf(d_k) = \frac{d_k - E(d_k)}{\sqrt{\text{Var}(d_k)}}, \quad (k = 1, 2, 3, \dots, n), \quad (3)$$

where $Uf(d_k)$ is the forward sequence, and the backward sequence $Ub(d_k)$ is calculated using the same equation but with a reversed series of data.

In the M-K test, a positive z value indicates an increasing trend and a negative value indicates a decreasing trend. A trend is statistically significant at the 0.05 and 0.01 significance levels when $|z| > 1.96$ and 2.576, respectively.

4. Results

4.1. Temporal Characteristics of Precipitation Extremes. The time series of extreme precipitation indices illustrate how precipitation extremes changed from 1960 to 2012 in the Poyang Lake basin. The variations of the threshold indices, including EPD, EPA, EPI, and EPR, in the basin during 1960–2012 are shown in Figure 2. Table 3 shows the results of corresponding M-K sequential test. It is seen that the EPD ranges from 11 days to 27 days and the EPA ranges between 461 mm and 1313 mm. Both of these indices show a long-term increasing trend in the study period with the M-K statistic of 1.27 and 1.42, respectively (Table 3). The increasing trend is especially significant before 2000. We also note slightly negative changes in the time series of EPD and EPA in the 2000s. The EPI varies between 40.7 mm/day in 1963 and 49.3 mm/day in 1998, with a significant trend of increase in the entire study period. It is also seen that the EPR ranges from 40 % in 1963 to 60% in 1998 and shows a significant increasing trend at the 0.05 significance level. The high values of the EPR indicate that the extreme precipitation plays a more important role in contributing to the annual rainfall in the Poyang Lake basin.

Figure 3 shows the results of the duration and absolute indices, including CDD, CWD, Rx1d, and Rx5d. The time series of CDD and CWD exhibit a little change and a slightly negative trend in the entire study period, with the M-K statistic of -0.03 and -1.01 , respectively (Table 3). We note that the trend in CDD is dominated by a peak in 1979 and also around the middle 2000s when extreme drought

occurred and the lake was nearly dried up. The Rx1d shows a general increase in trend from 1960 to 2012, with the M-K statistic of 0.68 (Table 3). The increase is more evident after the mid 1980s, but is not significant in recent years. The time series of Rx5d also exhibit a positive trend with large fluctuations, from 138 mm in 1979 to 289 mm in 1998. It is noted that several peaks such as in 1979, 1998, and 2010 correspond to the floods in the Poyang Lake with the lake level exceeding the warning stage by 1.19–3.53 m for 32–93 consecutive days during that period.

4.2. Spatial Characteristics of Precipitation Extremes. The spatial distribution of the average values of threshold indices during 1960–2012 is shown in Figure 4, and the mean values of extreme precipitation indices in five subcatchments in the Poyang Lake basin are shown in Table 4. It is seen that all the threshold indices exhibit large spatial differences across the Poyang Lake basin. For EPD, the low value is found in the western and southern areas where EPD is below 18 days at most stations. High EPD area is in the northeastern and eastern basin, where EPD is more than 21 days. The spatial distribution of extreme precipitation amount is similar to EPD. Regional average EPA ranges between 920.7 and 998.0 mm in Fuhe, Xinjiang, and Raohe subcatchment, but it is lower than 827 mm in the Xiushui and Ganjiang subcatchment (Table 4). Some lowest values of EPA are found in the south Ganjiang subcatchment. The precipitation intensity is also strong in the northeast, where the EPI has reached up to 47.8 mm/day in the Raohe subcatchment. The intensity is weak however in the south with the EPI below 42 mm/day. In addition, the contribution of extreme precipitation to the annual rainfall in the northeastern and eastern areas is higher than the other areas, with the EPR accounting for more than 52% (Figure 4). In general, the regional averaged values of EPD, EPA, EPI, and EPR in Fuhe, Xinjiang, and Raohe subcatchment are higher than that in the Xiushui and Ganjiang subcatchment (Table 4). Figure 4 and Table 4 indicate that the northeastern and eastern areas, i.e., Fuhe, Xinjiang, and Raohe subcatchment, have a higher frequency of extreme precipitation events than other areas in the Poyang Lake basin.

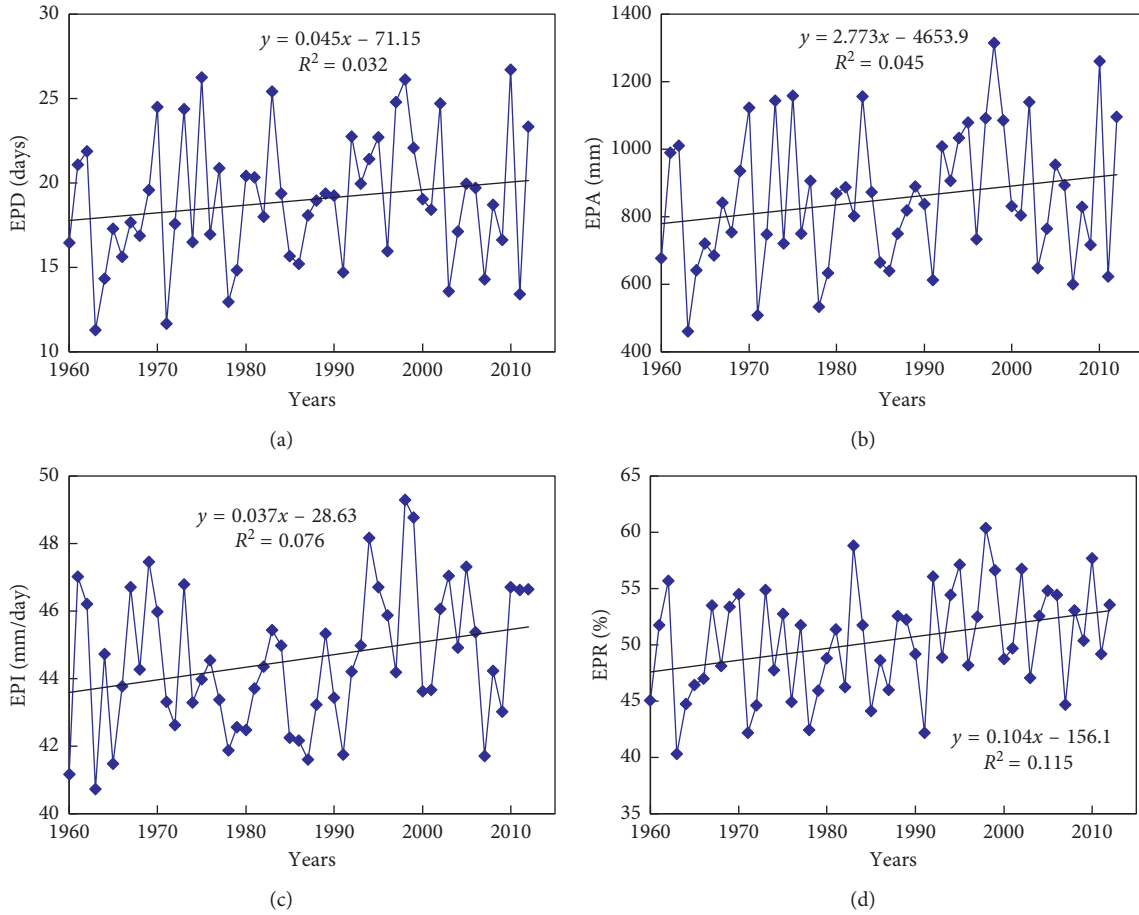


FIGURE 2: Variation of (a) EPD, (b) EPA, (c) EPI, and (d) EPR in Poyang Lake basin during 1960–2012.

TABLE 3: Results of M-K test for 8 extreme precipitation indices.

Index	EPD	EPA	EPI	EPR	CDD	CWD	Rx1d	Rx5d
M-K statistic	1.27	1.42	1.85*	2.54**	-0.03	-1.01	0.68	0.24

*Delineates significance at the 0.1 significance level and **delineates significance at the 0.05 significance level.

Figure 5 shows the spatial distribution of the average duration and absolute indices during 1960–2012. It is seen that the CDD exhibits large regional difference, ranging from about 22 days in the western areas to 34 days in the south. The spatial pattern of CWD is different from the CDD, the averaged value of which is 8.9 days in eastern and northeastern areas and is 8.3 and 8.7 days in the Xiushui and Ganjiang subcatchment, respectively (Table 4). In addition, the absolute indices present a similar spatial distribution to the threshold indices. Specifically, the Rx1d never exceeds 100 mm in the southern area but reaches to 140 mm in the northeastern area. Meanwhile, the Rx5d also ranges from about 150 mm in the south of the Ganjiang subcatchment to about 222 mm in the Raohe subcatchment (Table 4). Figure 5 further indicates that the Fuhe, Xinjiang, and Raohe subcatchments are exposed to high risk of flood disaster due to the high frequency of extreme precipitation events.

The spatial patterns of the extreme precipitation indices over the Poyang Lake basin are shown in Figures 6 and 7. The percentages of stations showing upward and downward trends for each extreme precipitation index are summarized in Table 5. It is seen that the EPD has increased at 66 (88.0%) of the 75 stations from 1960 to 2012, 7 (9.3%) of which is statistically significant at the 0.1 significance level (Table 5). The stations with upward trends are distributed fairly uniformly throughout the study area (Figure 6). Only 9 (12.0%) stations have downward trends, none of which is significant, and these stations are primarily located in the Ganjiang subcatchment. The spatial distribution of EPA trend is similar to EPD trend, with more than 90% of stations showing an upward trend in the study area. Only 7 (9.3%) stations in the southern basin have downward trend (Figure 6). Although the stations showing downward trends for EPI increase to 19 (25.3%) mainly in the Ganjiang subcatchment, 56 (74.7%) stations have upward trends. Among those stations, 9 (12.0%) are statistically significant at the 0.1 significance level (Table 5). As for the contribution of extreme precipitation, the EPR increases at 69 (92%) stations and 24 (32.0%) of which are statistically significant at the 0.1 significance level (Table 5). Several stations in the southern part of the Ganjiang subcatchment and surrounding region of the lake have downward trends, none of which is significant however (Figure 6).

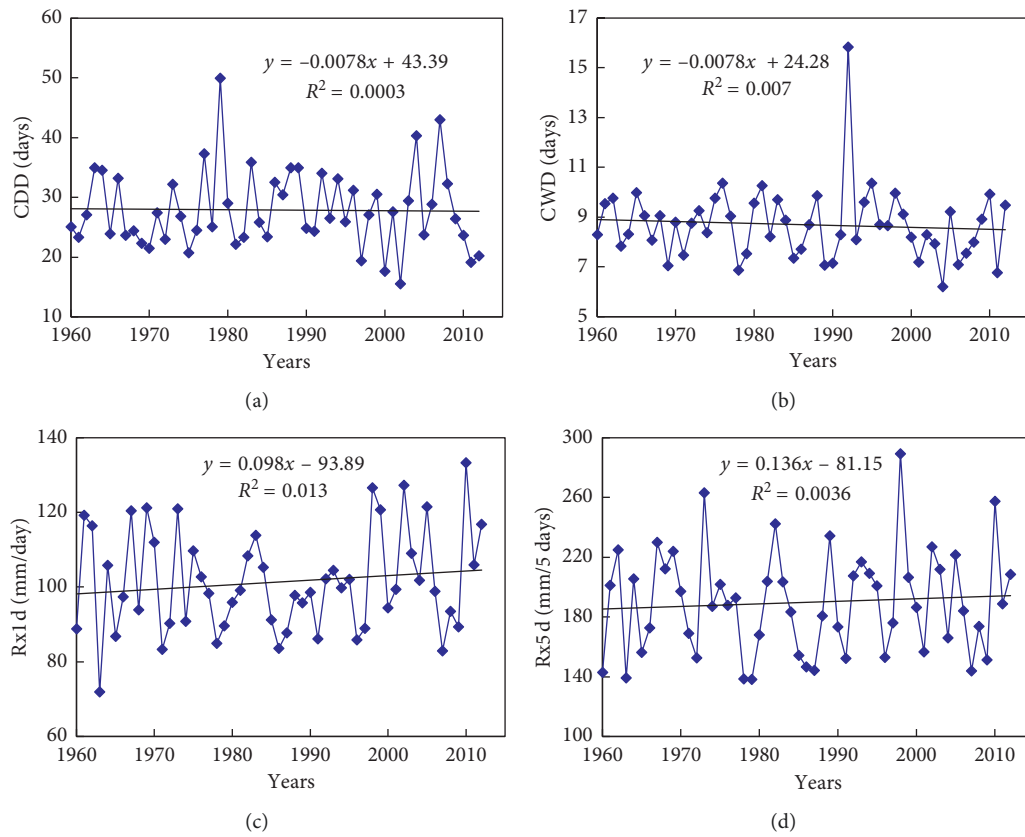


FIGURE 3: Variation of (a) CDD, (b) CWD, (c) Rx1d, and (d) Rx5d in Poyang Lake basin during 1960–2012.

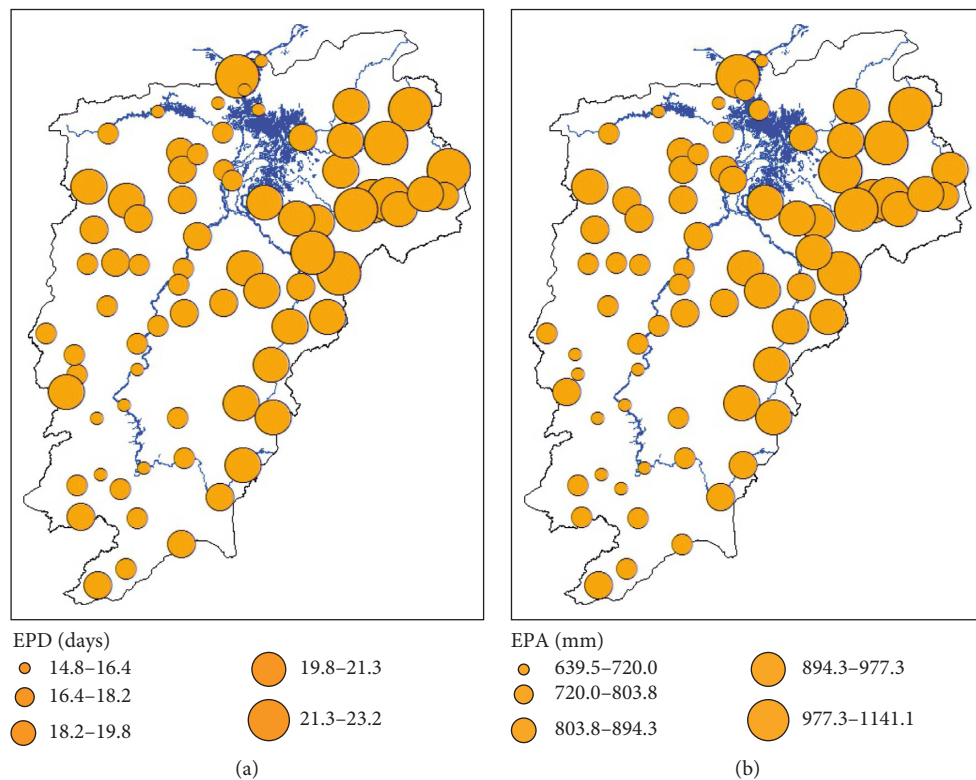


FIGURE 4: Continued.

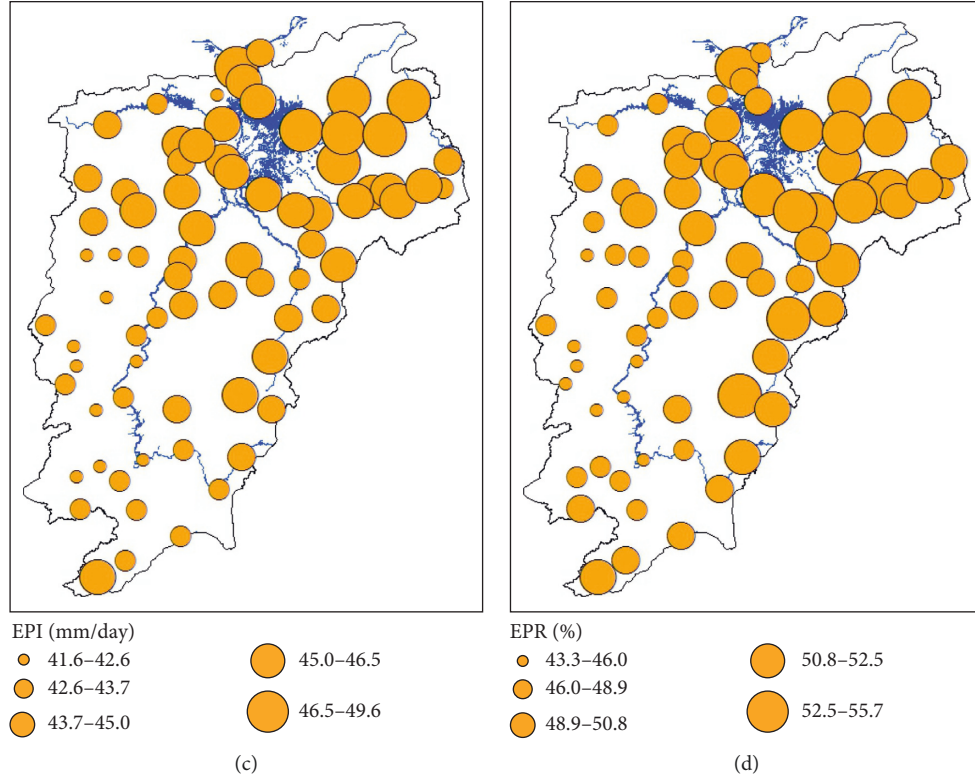


FIGURE 4: Spatial distributions of (a) EPD, (b) EPA, (c) EPI, and (d) EPR in Poyang Lake basin.

TABLE 4: Regional average of extreme precipitation indices for five subcatchments.

Subcatchment	EPD (days)	EPA (mm)	EPI (mm/day)	EPR (%)	CDD (days)	CWD (days)	Rx1d (mm)	Rx5d (mm)
Xiushui	18.3	826.7	44.9	50.3	27.2	8.3	101.3	189.2
Ganjiang	18.1	789.6	43.5	48.6	28.6	8.7	94.1	174.2
Fuhe	20.4	920.7	44.9	52.0	27.5	8.9	108.2	206.9
Xinjiang	21.5	990.7	45.6	52.4	25.7	8.9	106.3	215.8
Raohe	20.7	998.0	47.8	54.3	27.3	8.9	118.5	222.0
Whole basin	19.0	853.2	44.6	50.26	27.9	8.7	101.0	189.7

Compared to the threshold indices, the variation trends of duration and absolute indices are not as consistent in the Poyang Lake basin. Figure 7 shows that the CDD decreases at 45 (60%) of the 75 stations from 1960 to 2012. Among them, only 5 (6.7%) are statistically significant at the 0.1 significance level (Table 5). The remaining 30 (40.0%) stations have upward trend but none of them is significant. The spatial trends of CDD suggest that shorter dry spells are situated fairly uniformly throughout the study area, whereas upward trends are primarily in the Ganjiang subcatchment (Figure 7).

The CWD exhibits a similar spatial distribution to that of CDD, but with more stations (59 stations or 78.7%) showing a downward trend. Some stations with increasing trends are scattered in the southern part of the Ganjiang subcatchment and the surrounding areas of the lake (Figure 7).

For Rx1d and Rx5d, about two-thirds of the stations (48 station for Rx1d and 50 stations for Rx5d) display upward trends during 1960–2012. Eleven (14.7%) of the 48 stations show significant upward trends for Rx1d. The remaining

one-third of the stations have downward trends, and those stations are mainly found in the Ganjiang subcatchment and surrounding areas of the lake (Figure 7). Figures 6 and 7 indicate that the extreme precipitation conditions in the Poyang Lake basin are aggravating, especially in the northeastern and eastern areas, including Fuhe, Xinjiang, and Raohe subcatchments.

4.3. Relationship between Precipitation Extremes and Topography. The relationships between extreme precipitation indices at individual rain gauges and elevations in the Poyang Lake basin are shown in Figure 8. It is seen that all correlation coefficients (r) between the extreme precipitation indices and elevation have high year-to-year variability, with r ranging from -0.24 to 0.39 for EPD, -0.20 to 0.62 for EPA, -0.35 to 0.60 for EPI, -0.30 to 0.38 for EPR, -0.25 to 0.39 for CWD, -0.52 to 0.14 for CDD, -0.25 to 0.74 for Rx1d, and -0.32 to 0.77 for Rx5d. This variability is mainly associated with the characteristics of precipitation in

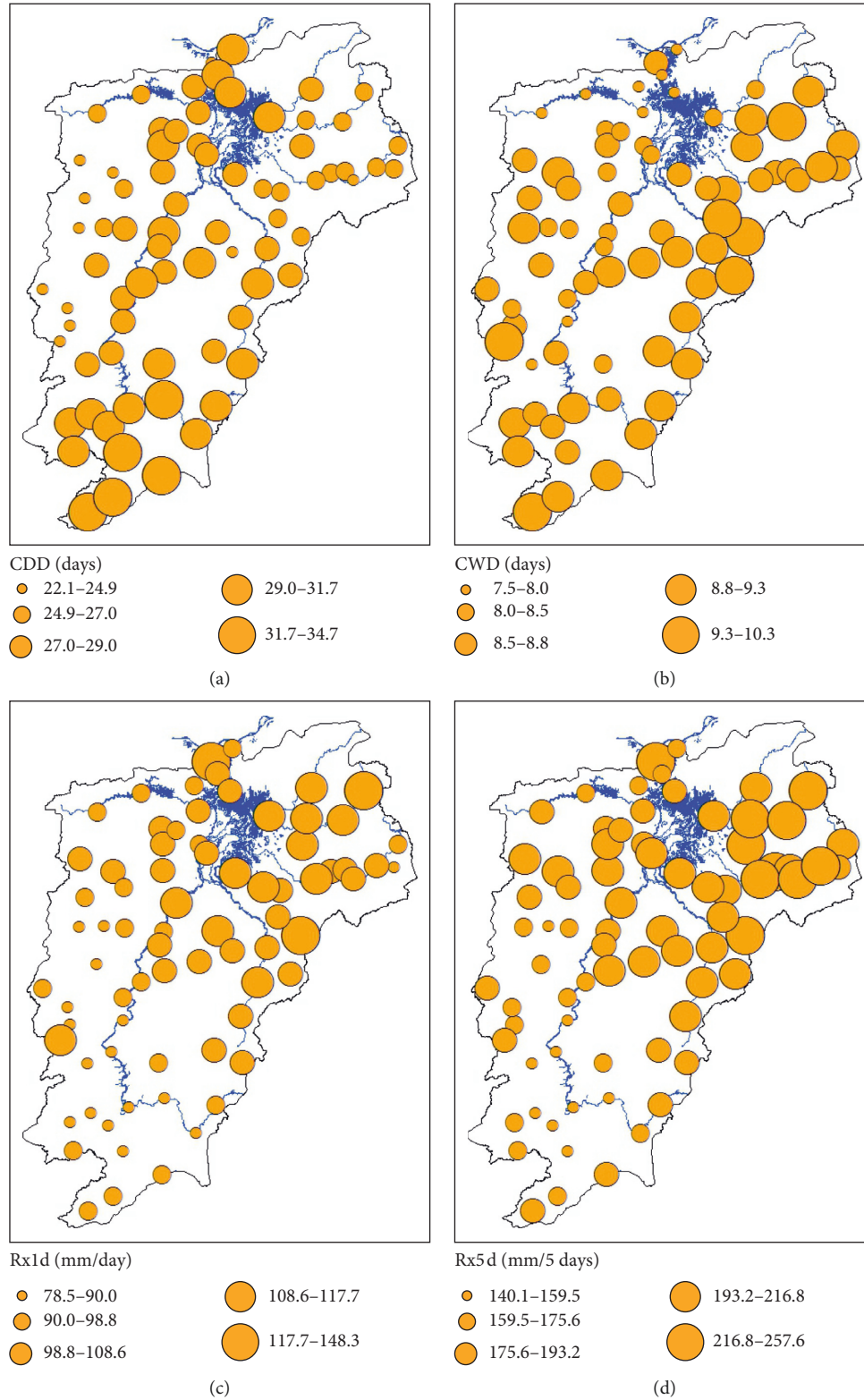


FIGURE 5: Spatial distributions of (a) CDD, (b) CWD, (c) Rx1d, and (d) Rx5d in Poyang Lake basin.

different years. In general, among these indices, except the CDD which has negative correlation with elevation in principle, the others present positive correlation with the elevation. The correlation coefficients are especially high in

1984 and 2005. These results indicate that the value of these indices increases as the elevation increases. Figure 8 reveals that elevation is also an important factor affecting the variability of precipitation extremes over the Poyang Lake basin.

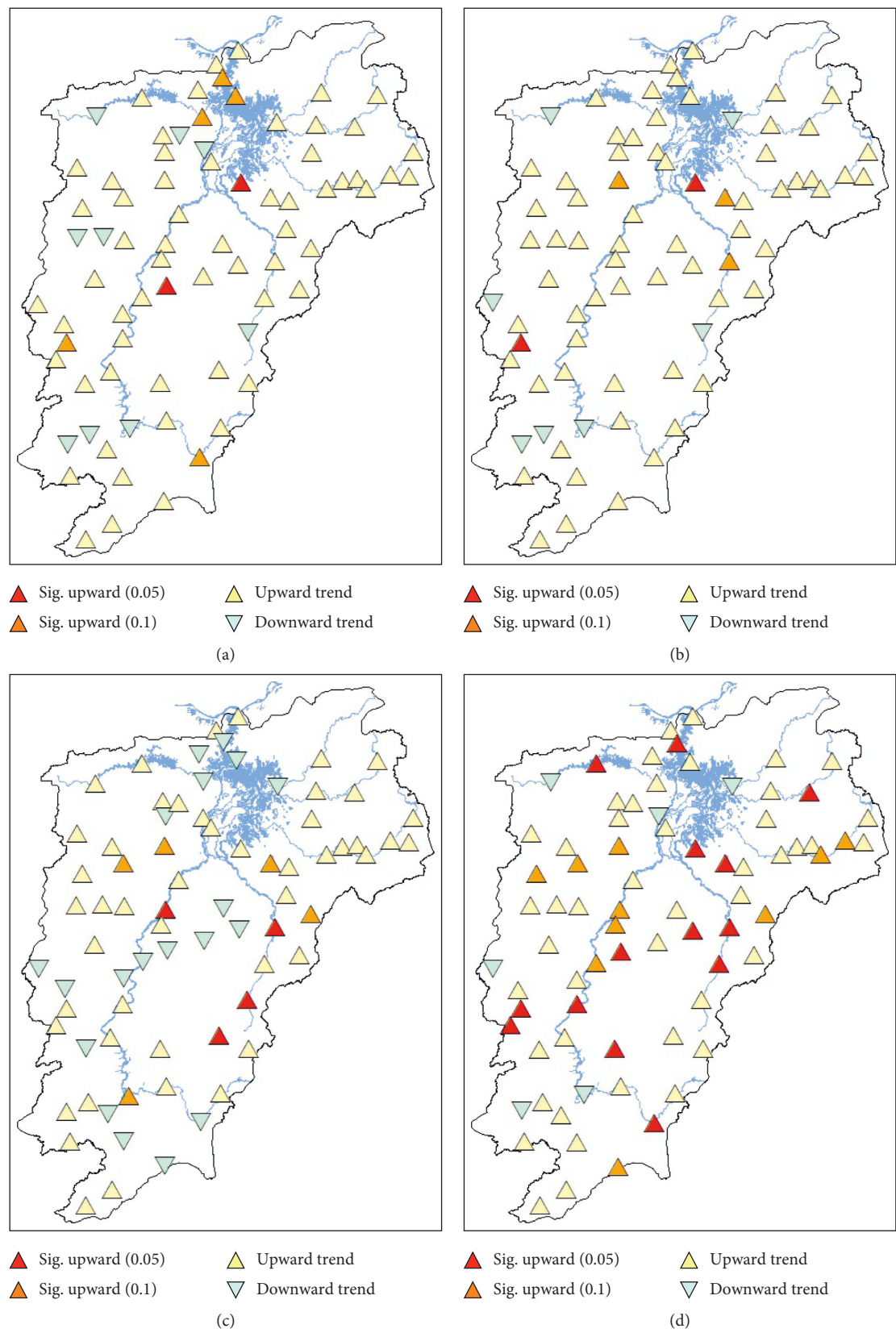


FIGURE 6: Spatial patterns of long-term trends for (a) EPD, (b) EPA, (c) EPI, and (d) EPR in the Poyang Lake basin during 1960–2012.

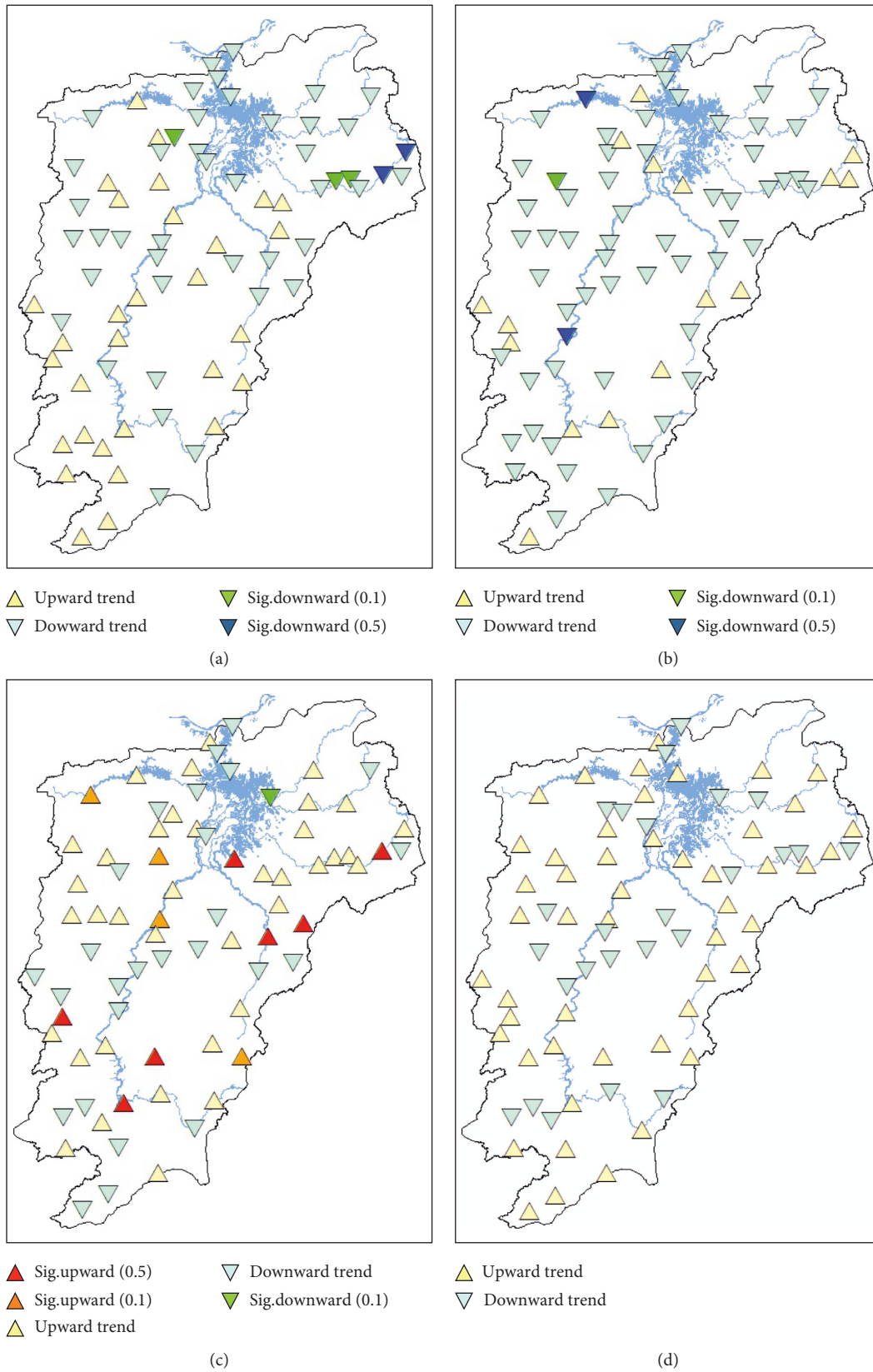


FIGURE 7: Spatial patterns of long-term trends for (a) CDD, (b) CWD, (c) Rx1d, and (d) Rx5d in the Poyang Lake basin during 1960–2012.

TABLE 5: Number and percentage of stations showing upward and downward trends for each extreme precipitation index.

Index	Upward trend			Downward trend		
	Not sig.	Sig. at 0.1	Total	Not sig.	Sig. at 0.1	Total
EPD	59 (78.7%)	7 (9.3%)	66 (88.0%)	9 (12.0%)	0 (0)	9 (12.0%)
EPA	63 (84.0%)	5 (6.7%)	68 (90.7%)	7 (9.3%)	0 (0)	7 (9.3%)
EPI	47 (62.7%)	9 (12.0%)	56 (74.7%)	19 (25.3%)	0 (0)	19 (25.3%)
EPR	45 (60.0%)	24 (32.0%)	69 (92.0%)	6 (8.0%)	0 (0)	6 (8.0%)
CDD	30 (40.0%)	0 (0)	30 (40.0%)	40 (53.3%)	5 (6.7%)	45 (60.0%)
CWD	16 (21.3%)	0 (0)	16 (21.3%)	56 (74.7%)	3 (4.0%)	59 (78.7%)
Rx1d	37 (49.3%)	11 (14.7%)	48 (64.0%)	26 (34.7%)	1 (1.3%)	27 (36.0%)
Rx5d	50 (66.7%)	0 (0)	50 (66.7%)	25 (33.3%)	0 (0)	25 (33.3%)

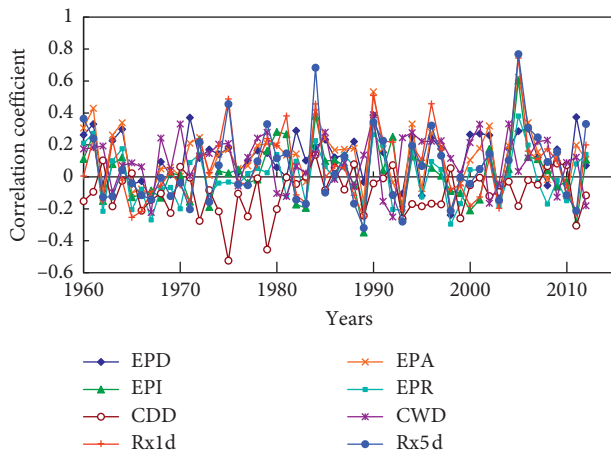


FIGURE 8: Variation of correlation coefficients between the extreme precipitation indices and elevation.

Table 6 shows the average values of each index in the categorized elevation groups. There are six indices with the largest value appearing at elevation >300 m. The indices of EPA, Rx1d, and Rx5d are much higher in the elevation groups, a result indicating that the precipitation extremes are intensifying at higher elevation. Generally, the higher altitude such as mountains helps increase precipitation, because topography can change the propagation direction of atmospheric moisture and increase rainfall and also reduce evaporation of rainfall.

The statistical relationship between the extreme precipitation trends during 1960–2012 and elevation in the Poyang Lake basin is summarized in Table 7. It is seen that, for the threshold indices EPD, EPA, EPI, and EPR, over 30 of the 40 stations show an upward trend at the group of low elevation (<100 m). Most of the stations also display upward trend at the middle elevation group (100–200 m and 200–300 m), although the number of stations with upward trend is less than that in the low elevation group. An intriguing result is that almost all stations show the upward trend at the high elevation group (>300 m). Duration indices (CDD and CWD) exhibit generally an opposite distribution to the threshold indices. Most stations present a clear downward trend at the elevation group of <100 m and >300 m. Although the Rx1d and Rx5d exhibit a similar distribution to that of the threshold indices, i.e., the most stations show upward trend at the elevation group of <100 m, the number

of stations with downward trend are also largest in the same elevation group. Results in Table 7 indicate that the extreme precipitation has an increase trend at stations with elevation <100 m or >300 m but a decrease trend at 100–200 m elevation range.

5. Discussion

The previous sections present the trends and spatial variability of extreme precipitation events in the Poyang Lake basin. The results show that the precipitation extremes are intensified during 1960–2012. In particular, the increasing trends are significant before the year 2000, and high values of EPR indicate that the extreme precipitation played a more important role in contributing to the annual rainfall of the Poyang Lake basin. As such, the northeastern and eastern areas of the basin, including Fuhe, Xinjiang, and Raohe subcatchments, are exposed to high risk of floods because of the higher frequency of extreme precipitation events. The increasing frequency of precipitation extremes and its uneven distribution in the lake basin are consistent with the previous studies in the same area [3, 17, 37, 48, 65]. A strong factor influencing these spatiotemporal distributions in extreme precipitation trends could be the changing climate. According to the analysis of Ye et al. [66] and Zhang et al. [67], the mean temperature in the Poyang Lake basin shows a long-term increasing trend at the rate of $0.1\text{--}0.16^\circ\text{C}$ per decade, due to the intensified global warming and rapid local industrial development during the last five decades. Zhang et al. [65] reported that the intensifying precipitation extremes occurred mainly in the north of the Poyang Lake basin, a finding in agreement with areas dominated by increasing temperature. This increase in extreme precipitation events is consistent with expected impacts of climate change on precipitation, i.e., heavier precipitation resulting from the increasing ability of the atmosphere to hold more water as described by the Clausius–Clapeyron relationship [68].

Furthermore, Zou and Ren [69] reported that the East Asian summer monsoon (EASM) has a significant influence on precipitation extremes, especially for the middle and lower reaches of the Yangtze River. Many studies have identified the impacts of EASM on precipitation changes in eastern China and indicated that the weakening of the EASM after the end of the 1970s remarkably increased summer precipitation in the middle and lower Yangtze River basin [65, 70–72]. The Poyang Lake basin is strongly influenced by

TABLE 6: Average values of extreme precipitation indices in the categorized elevation groups.

Elevation (m)	EPD (days)	EPA (mm)	EPI (mm/day)	EPR (%)	CDD (days)	CWD (days)	Rx1d (mm)	Rx5d (mm)
<50	18.0	824.6	45.4	51.2	28.6	8.2	104.4	189.8
50–100	19.6	886.8	44.9	50.8	27.0	8.7	102.9	198.0
100–150	18.5	813.6	43.8	48.8	27.7	8.8	95.2	181.1
150–200	18.1	784.0	43.2	48.6	29.0	8.6	93.1	175.0
200–250	19.8	883.2	44.2	51.1	30.3	9.1	102.7	188.1
250–300	18.8	830.0	43.9	48.7	27.4	8.9	95.7	184.0
>300	20.5	946.4	45.5	50.6	26.1	9.4	118.4	207.3

TABLE 7: Distribution of stations showing upward and downward trends in the categorized elevation groups.

Elevation group (m)	Number of stations	Trend	EPD	EPA	EPI	EPR	CDD	CWD	Rx1d	Rx5d
<100	40	Upward	38	40	30	38	11	5	24	22
		Downward	2	0	10	2	29	35	16	18
100–200	22	Upward	17	18	14	19	11	9	14	18
		Downward	5	4	8	3	11	13	8	4
200–300	10	Upward	9	9	10	9	8	3	7	8
		Downward	1	1	0	1	2	7	3	2
>300	3	Upward	3	3	2	3	1	0	3	3
		Downward	0	0	1	0	2	3	0	0

the EASM. When a larger amount of atmospheric moisture is transported from East or South China Sea by the monsoon circulation, there is likely to have more heavy rainfall [3]. Weakening in the EASM would limit its northward extension and keep a longer rainy season in southern China. This position favors a steady increase in not only the total rainfall but also the extreme precipitation events in summer in the Poyang Lake basin [36, 56, 73]. Hu et al. [45] and Guo et al. [46] also showed that the increase in heavy and extreme precipitation events in the Poyang Lake basin in the 1990s was partially attributable to the southward shift of warm-season rain bands to the south of the Yangtze River basin.

The El Niño-Southern Oscillation (ENSO) event is another factor that may contribute to the changes and trends of extreme precipitation in this region. Recent studies of ENSO have identified a remarkable climatic link between extreme precipitation and both the warm (El Niño) and cold (La Niña) phases of Southern Oscillation in various areas of the world [65, 72, 74]. Duan et al. [75] found that during the rainy season in southern China, warm ENSO episodes can promote the convergence of the water vapor flux, boosting the moisture content and hence the likelihood of extreme precipitation events. Zhang et al. [48] revealed that the correlation between the absolute indices Rx1d and Rx5d and ENSO is statistically positive in the Poyang Lake basin, and they are influenced mainly by the ENSO events with a one-year time lag. They further showed that the occurrence of ENSO can amplify the variability of extreme precipitation in summer [48]. Shankman et al. [42] also found that the most severe floods in the Poyang Lake since 1950 occurred during or immediately following El Niño events. The extreme precipitation in the Poyang Lake basin is also been influenced by the North Atlantic Oscillation (NAO), Indian Ocean Dipole (IOD), and Pacific Decadal Oscillation (PDO) [76–78]. Linderholm et al. [76] have revealed that the climate

patterns in summer over China are connected with the interannual changes of the summer NAO. Xiao et al. [72] also found that the negative PDO event at the same year tends to increase the occurrence of precipitation events in spring, and both the occurrence and intensity of precipitation events during summer and autumn months have been influenced by the ENSO and IOD. Xiao et al. [72] further pointed out that the influences of ENSO, NAO, IOD, and PDO on the seasonal occurrence and intensity of precipitation events are complex.

In addition, this study also shows that the extreme precipitation indices had strong positive correlations with regional features of terrain elevation. This finding is in agreement with the results of Zhang et al. [48], who showed that higher elevations in the Poyang Lake basin often coincide with higher Rx1d in summer and autumn. Zhang and Liu [79] also found that Rx1d and Rx5d are generally positively correlated with the mean elevation and slope rate, in the adjacent region of the Poyang Lake basin (the Dongting Lake basin). Similar results are also reported in studies by Wang et al. [25], Guan et al. [17], and Li et al. [80]. However, Zhang et al. [48] further pointed out that the influences of orography on changes of extreme precipitation are complicated. Therefore, further work needs to be carried out in the future to address more detailed assessments of the interrelationship between topography and extreme precipitation variation trends.

6. Conclusions

This study used a suite of extreme precipitation-related indices and analyzed the trend and variability of extreme precipitation from 1960 to 2012 in the Poyang Lake basin and the relationship of extreme precipitation with basin's elevation and orography. Results show that extreme

precipitation in the Poyang Lake basin intensified during the last five decades. Except for CDD and CWD which exhibit a slightly negative trend in the study period, the other indices, including EPD, EPA, EPI, EPR, Rx1d, and Rx5d, show continuous increase trends at the rate of 0.45 days, 27.73 mm, 0.37 mm/day, 1.04%, 0.13 mm, and 1.36 mm per decade, respectively. The increasing trends are especially strong before the year 2000. Moreover, high values of EPR (ranging between 40 and 60%) indicate that the extreme precipitation plays a more important role in contributing to the annual precipitation and water resources of the Poyang Lake basin.

The precipitation extremes in the Poyang Lake basin exhibit a significant spatial variation. The averaged values of extreme precipitation indices of the Fuhe, Xinjiang, and Raohe subcatchments are higher than the other areas, a result indicating that the northeastern and eastern regions of the Poyang Lake basin have a rising frequency of extreme precipitation events. Analysis of spatial trends reveals that the ground stations with upward trends are distributed fairly uniformly in the basin. Stations with the downward trend are clustered in the Ganjiang subcatchment. This spatial pattern indicates that the extreme precipitation has become more frequent in many areas of the lake basin, except for the Ganjiang subcatchment, and the extreme precipitation conditions are more aggravated than in the early decades. These variations and trends of precipitation extremes in time and space in the Poyang Lake basin are largely associated with the changing climate and embedded EASM.

In addition, except for the CDD which is found to have negative correlation with elevation, the other extreme precipitation indices have shown strong positive correlations with the elevation. For threshold indices EPD, EPA, EPI, and EPR, over 30 of the 40 stations with low elevation (<100 m) and almost all stations with high elevation (>300 m) in the basin show an upward trend. CDD and CWD exhibit an opposite distribution to the threshold indices. As for Rx1d and Rx5d, the largest number of stations is found in the elevation group of <100 m, regardless of upward trends or downward trends. The complex influences of orography on changes in extreme precipitation indicate that more work is needed to further understand them.

Data Availability

All relevant data can be obtained from the National Meteorological Information Center of China (<https://data.cma.cn>).

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this article.

Acknowledgments

This work was jointly funded by the National Natural Science Foundation of China (41571023 and 41871093) and the Key Program of Nanjing Institute of Geography and Limnology of the Chinese Academy of Sciences (NIGLAS2018GH06).

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